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PILOT LINE REPORT

Development of a High Efficiency Thin Silicon Solar Cell

JPL Contract No. 954883

July, 1980

Report No. SX/115/PL-2

BY

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology Sponsored by the National Aeronautics and Space Administration under Contract NAS-7100.

TECHNICAL CONTENT STATEMENT

ABSTRACT

During the period of this contract, alternate processing technologies were developed and introduced into the Pilot Line with a resulting increase in the efficiency of the thin cells. The introduction of an aluminum paste alloy technique for the formation of a back surface field represents a significant advance over previous techniques. This Pilot Line report describes the fabrication and results for quantities in excess of 2000 2 cm x 2 cm Thin Cells and 1000 5 cm x 5 cm Thin Cells. A major goal was to demonstrate that high efficiency cells could be fabricated with acceptable yields. Substantial improvement in performance and yield of the Thin Cells were obtained. The overall yield of the 2 cm x 2 cm Pilot Line was better than 38%, while the best lot yield was greater than 51%. The average power density of the 2 cm x 2 cm cells was approximately 16.8 mW/cm^2 with an average AMO (at 25°C) efficiency of 12.4%. The lot yield of the 5 cm x 5 cm Pilot Line improved from only 7% at the beginning of the operation to better than 17% as experience was gained. The average 5 cm x 5 cm Thin Cell had an AMO efficiency (at 25°C) of 11.5%.

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1. INTRODUCTION

In 1976, Solarex showed that ultrathin silicon solar cells, 50 micrometers or less in thickness, could be fabricated in the laboratory.(1) Several hundred of these cells were delivered to Jet Propulsion Laboratory at that time. NASA-OAST, recognizing the importance of this advance in silicon solar cell technology, then directed funding to support pilot line production. In a follow-on contract, Solarex assembled and began operating a pilot line facility in less that three months.(2) Figures 1-1 and 1-2 show the yield and AMO power at 25°C vs. lot number experienced in the first exercise of the pilot line facility. Yields improved considerably during the pilot line operation, increasing to more than 60% by the end of the operation. Output power remained consistent throughout. In parallel experimental efforts, 4 cm^2 cells were fabricated whose output power exceeded 67 mW.

In a subsequent contract,(3) the Pilot Line was utilized to implement advances in cell technology and to demonstrate a capability for fabricating 4 cm^2 ultra-thin cells at a 10,000 per month rate. Also, experimental quantities of large area (25 cm^2) ultra-thin cells were fabricated in order to determine their manufacturing feasibility. Figure 1-3 shows a plot of the AMO power versus the quarter of the

Figure 1 - 1

PILOT LINE YIELD

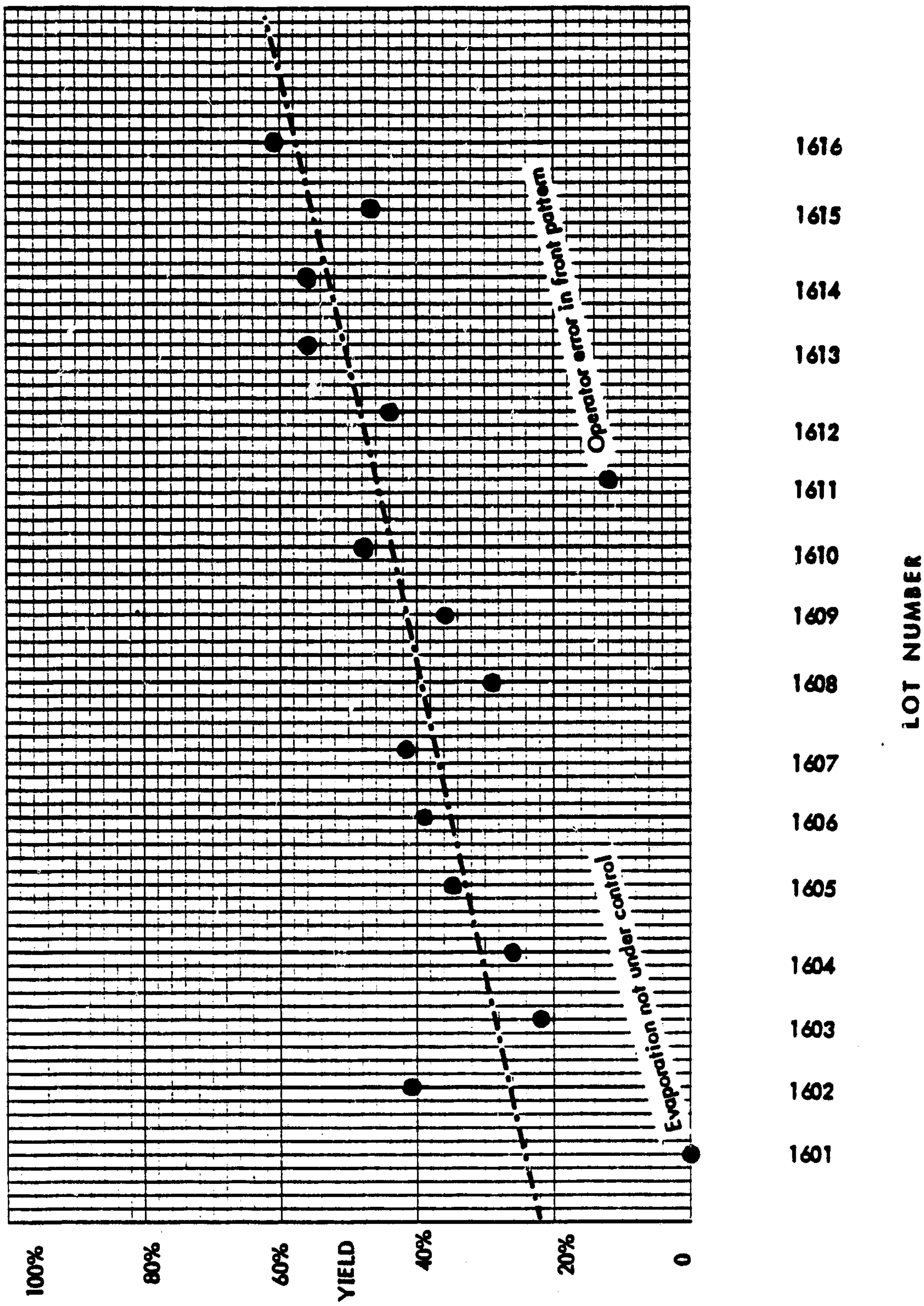
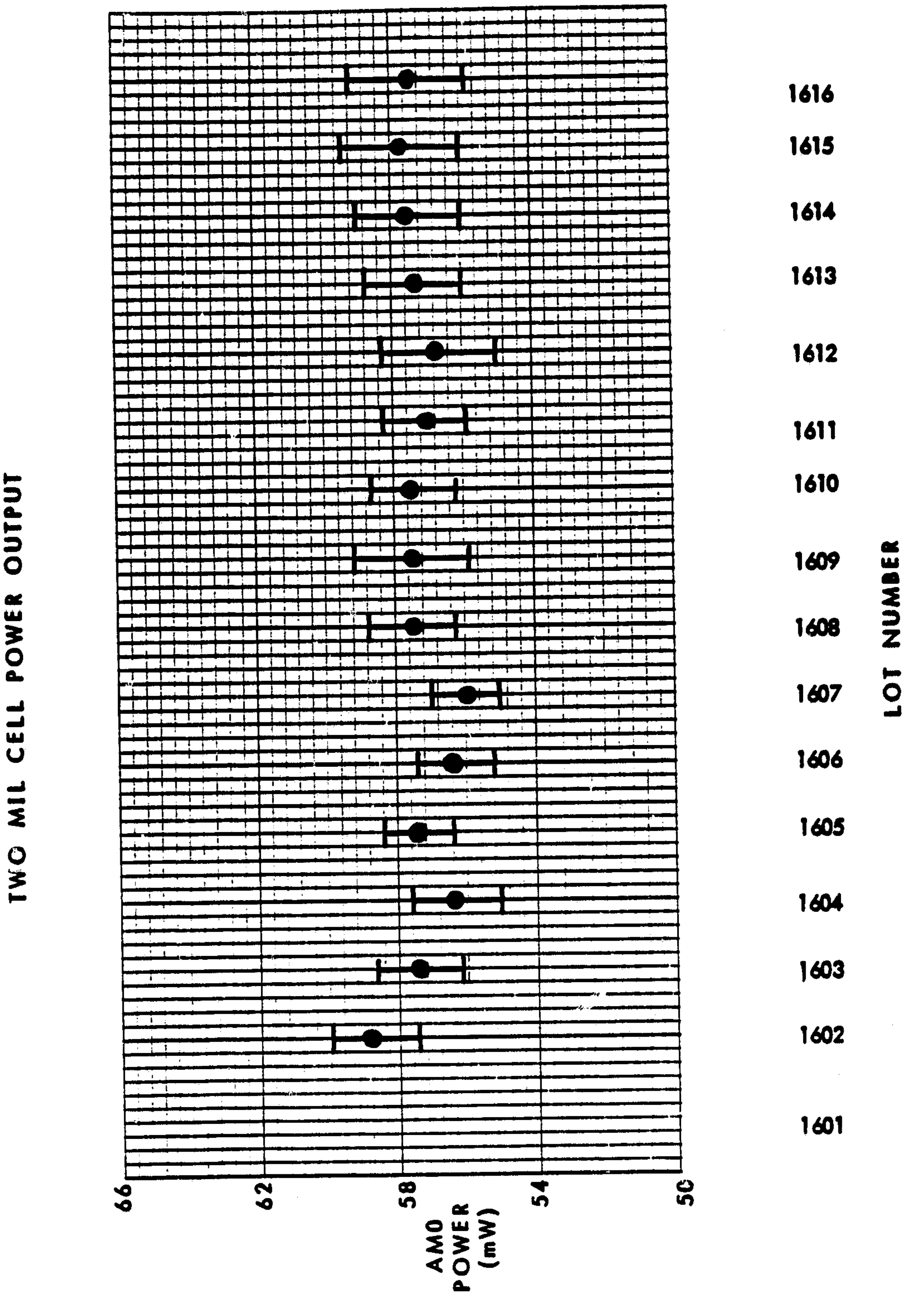


Figure 1 - 2

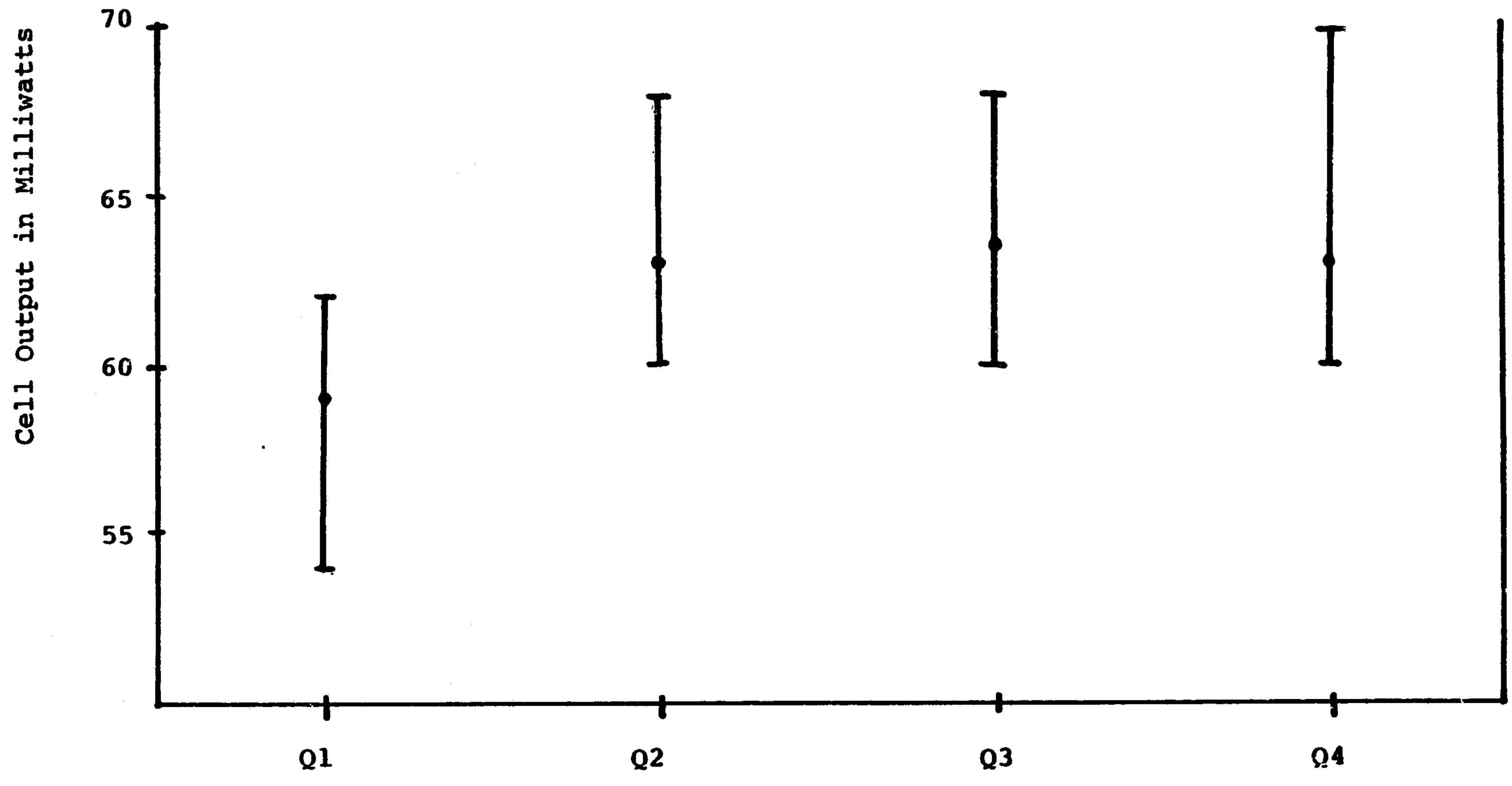


TWO MIL CELL POWER OUTPUT
LOT NUMBER
1616
1615
1614
1613
1612
1611
1610
1609
1608
1607
1606
1605
1604
1603
1602
1601
66
62
58
54
50
AM0 POWER (mW)

Figure 1 - 3

TYPICAL CELL POWER AT AM0

(The minimum, average and maximum values are all averages of the values of each lot).



contract in which the Pilot Line was operational. Each of the first three quarters represents results from 1000 cells and the last quarter, 2000 cells. As can be seen, a significant increase in average power occurred in the second quarter, primarily as a result of implementing an advance in processing technology. (See reference 3,4 on the effects of orientation of silicon slices during diffusion.) Yields for all four quarters were low (not exceeding 35% for any quarter) due to the start-stop nature of operation and, in the third quarter, to high personnel turnover. However, a production rate of 10,000 cells per month was demonstrated. In parallel experimental efforts, AMO cell efficiencies exceeding 14.5% (P_{max} = 79mW) were achieved with textured ultra-thin cells. From this work, it was clear that the substantial increases in output power could be transferred to cells fabricated on the Pilot Line.

During the period of this contract alternate processing technologies were developed which consistently resulted in high efficiency cells on high resistivity (7-14 ohm-cm) base material.[5] The introduction of the aluminum paste alloy technique for the formation of a back surface field represented a significant advance over previous techniques. As a consequence, in the present contract effort reported herein, the primary purpose was to implement these advances in processing technology in the Pilot Line Operation.

In this instance, 2000, 4 cm^2 and 1000, 25 cm^2 ultra-thin cells were to be fabricated. Also, a major goal was to demonstrate that high efficiency cells could be fabricated with acceptable yields (>50% in the case of 4 cm^2 cells)

2. Pilot Line Process Description

2.1. 2 cm x 2 cm Pilot Line

A process flow chart for the 2 cm x 2 cm Thin Cell Pilot Line is shown in Figure 2-1. Standard processing techniques were used throughout. The starting material was 7 to 14 Ω-cm, p-type, boron doped, CZ-grown silicon. The wafers were etched to 50 μm thickness by the following procedure: First, the wafers were sorted into 7 μm groups (e.g., 300 $\pm$3.5 μm) with an ADE 6033 thickness gauge. A group was etched in a 30% NaOH (110°C) solution to approximately 100-125 μm. After determining the batch thickness, and therefore the etch rate, etching was continued until the 50 μm thickness was achieved. Wafers were phosphorous diffused to approximately 100 Ω/□ , then etched in HF to remove the diffusion glass. The diffused wafers were printed with Englehard A3484 aluminum paste, baked at 225°C for 20 minutes, then alloyed at 850° for 25 seconds. The unalloyed aluminum was removed using a HCl etch, and any oxides were stripped by a quick HF etch. Ti/Pd was then evaporated onto this back surface. Front contact metallization was accomplished using Ti/Pd evaporated onto a pattern defined by photolithography. Excess metal was removed using an acetone lift-off bath. Approximately 9 to 10 microns of silver were then electroplated onto the Ti/Pd contacts.

Figure 2-1. 2 cm x 2 cm Process Diagram

THINNING ETCH

↓

DIFFUSION

↓

HF ETCH

↓

SCREEN PRINT Al BACK

↓

ALLOY Al BACK

↓

HCl ETCH

↓

Ti/Pd EVAPORATION - BACK

↓

PHOTOLITHOGRAPHY - FRONT

↓

Ti/Pd EVAPORATION - FRONT

↓

FRONT METALLIZATION LIFT-OFF

↓

Ag PLATING

↓

SINTER

↓

CUT TO SIZE

↓

CLEAN-UP

↓

AR COATING

↓

SINTER

↓

ELECTRICAL TEST

After sintering the metallizations, the wafers were cut into 2 cm x 2 cm cells, which were subsequently cleaned in an isopropanol bath. A TAO_x AR coating was evaporated and sintered at ~475°C for about 30 seconds. Completed cells were then tested with a Xenon simulator calibrated by reference cells.

2.2 5 cm x 5 cm Pilot Line

Pilot Line processing of the 5 cm x 5 cm thin cells was in many aspects identical to the 2 cm x 2 cm cells. However, since a large number of losses were anticipated in the latter process steps, the 50 μm thick wafers were attached to thick carrier wafers using cyanoacrylate adhesive after the back Ti/Pd evaporation and Ag plating. The wafers were therefore reinforced during the photolithography, front Ti/Pd evaporation and Ag plating, and cutting steps. The cyanoacrylate adhesive was chosen because it decomposes at approximately 300°C and, therefore, wafers or cells could be readily removed from the reinforcing carrier wafer during a sinter operation.

A flow chart of the 5 cm x 5 cm Thin Cell Pilot Line is shown in Figure 2-2.

Figure 2-2. 5 cm x 5 cm Process Diagram

THINNING ETCH

↓

DIFFUSION

↓

HF ETCH

↓

SCREEN PRINT Al BACK

↓

ALLOY Al BACK

↓

HCl ETCH

↓

Ti/Pd EVAPORATION - BACK

↓

Ag PLATING - BACK

↓

GLUE TO CARRIER WAFER

↓

PHOTOLITHOGRAPHY - FRONT

↓

Ti/Pd EVAPORATION - FRONT

↓

FRONT METALLIZATION LIFT-OFF

↓

Ag PLATING - FRONT

↓

CUT TO SIZE

↓

CLEAN-UP

↓

AR COATING

↓

SINTER

↓

ELECTRICAL TEST

3. Results

3.1 Cell Characteristics:

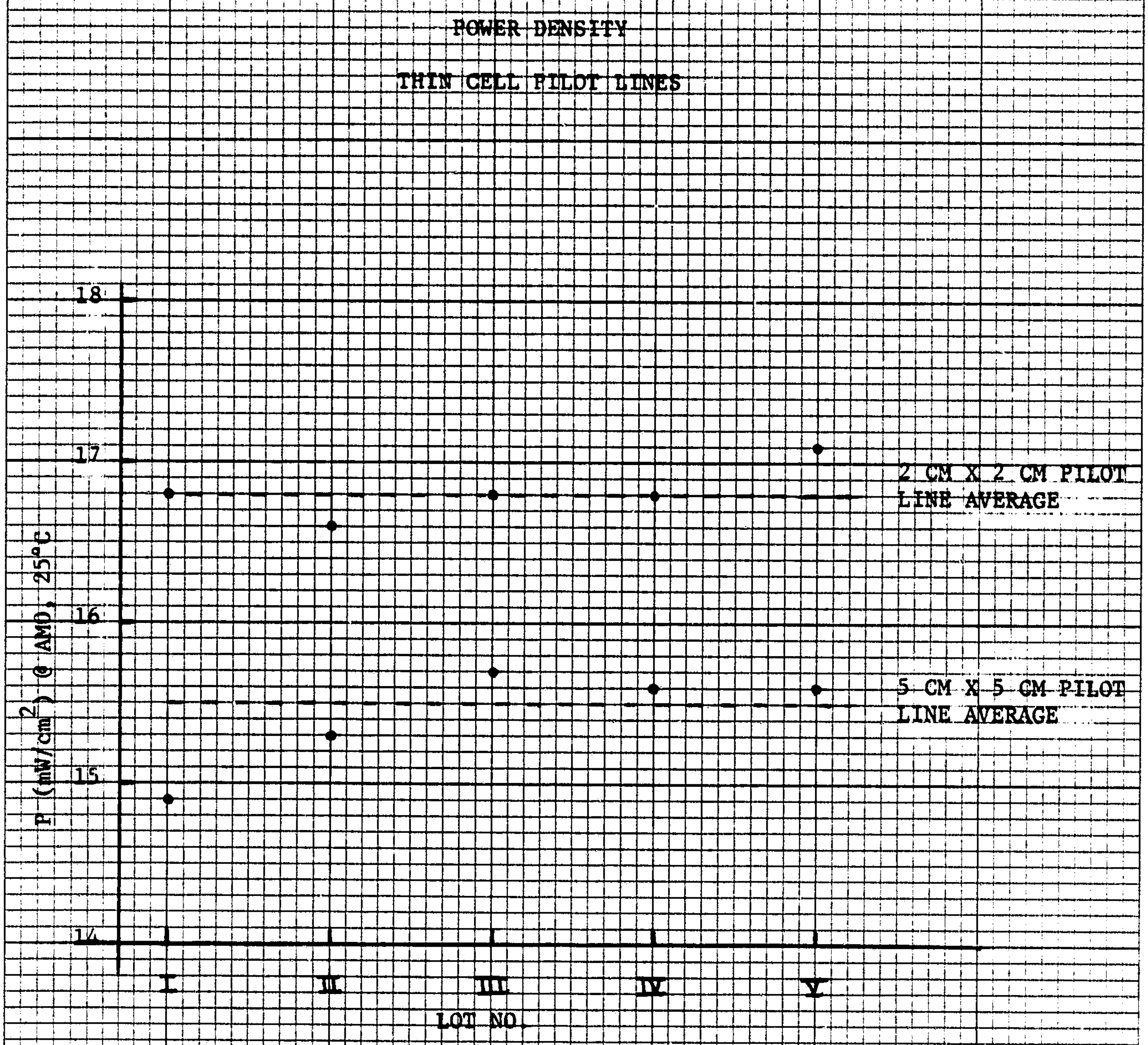
3.1.1 Output Power

Throughtout the operation of the 2 cm x 2 cm Thin Cell Pilot Line, the AMO power density at 25°C for each lot consistently averaged approximately 16.8 mW/cm^2 as shown in Figure 3-1. In contrast to the 2 cm x 2 cm Pilot Line effort, the AMO power density of the 5 cm x 5 cm Thin cells increased in Lots II and III from 14.9 mW/cm^2 to 15.7 mW/cm^2. Lots IV and V maintained this power while experiencing improved yields. Figure 3-1 shows the average power density by lot. The average power density for the 5 cm x 5 cm Pilot Line effort was 15.5 mW/cm^2.

3.1.2 V_{oc}, I_{sc}, FF

Tables 3-1 and 3-2 summarize the electrical performance (at AMO and 25°C) by lot for the 2 cm x 2 cm and 5 cm x 5 cm Thin Cell Pilot Lines, respectively. The Pilot Line averages are also included in these tables: the average 2 cm x 2 cm Pilot Line cell had an open-circuit voltage of 590 mV, a short-circuit current density of 36.5 mA/cm^2, and a fill-factor of 0.78, while the average 5 cm x 5 cm Pilot Line

Firgure 3 - 1



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K+E 10 X 10 TO THE INCH • 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

Table 3 - 1

2 CM X 2 CM THIN CELL ELECTRICAL PERFORMANCE (AMO, 25°C)

LOT	N (CELLS)	V_{oc} (mV)	J_{sc} (mA/cm^2)	P (mW/cm^2)	FF	η (%)
I	341	590	36.5	16.8	.78	12.5
II	347	589	36.0	16.6	.78	12.3
III	491	587	36.6	16.8	.78	12.4
IV	574	591	36.4	16.8	.78	12.5
V	524	592	37.0	17.1	.78	12.6
PILOT LINE	2277	590	36.5	16.8	.78	12.5

Table 3 - 2

5 CM X 5 CM THIN CELL ELECTRICAL PERFORMANCE (AMO, 25°C)

LOT	N (CELLS)	V_{oc} (mV)	J_{sc} (mA/cm^2)	P (mW/cm^2)	FF	η (%)
I	21	591	32.5	14.9	.78	11.1
II	30	596	33.1	15.3	.78	11.3
III	27	599	33.7	15.7	.78	11.6
IV	49	590	34.0	15.6	.78	11.6
V	32	593	33.3	15.6	.79	11.5
PILOT LINE	159	593	33.5	15.5	.78	11.5

cell had an open-circuit voltage of 593 mV, a short-circuit current density of 33.5 mA/cm^2, and a fill-factor of 0.78.

The variation of average open-circuit voltage and short-circuit current density by lot is shown in Figures 3-2 and 3-3. The fill factor did not vary much but was maintained at 0.78 for nearly every lot.

3.1.3 Cell Weight and Specific Power

A random sampling of 2 cm x 2 cm and 5 cm x 5 cm thin cells was weighed to obtain the average cell weight. The average 2 cm x 2 cm cell weighed 51.7 mg, while the average 5 cm x 5 cm cell weighed 406.9 mg. The specific power of the 2 cm x 2 cm Thin Cell was measured to be 1.30 kW/kg; the specific power of a 5 cm x 5 cm Thin Cell is 0.95 kW/kg.

3.2 Process Yields

3.2.1 Acceptance Criteria

The following criteria and procedures were established to monitor the quality of thin cells:

Figure 3 - 2

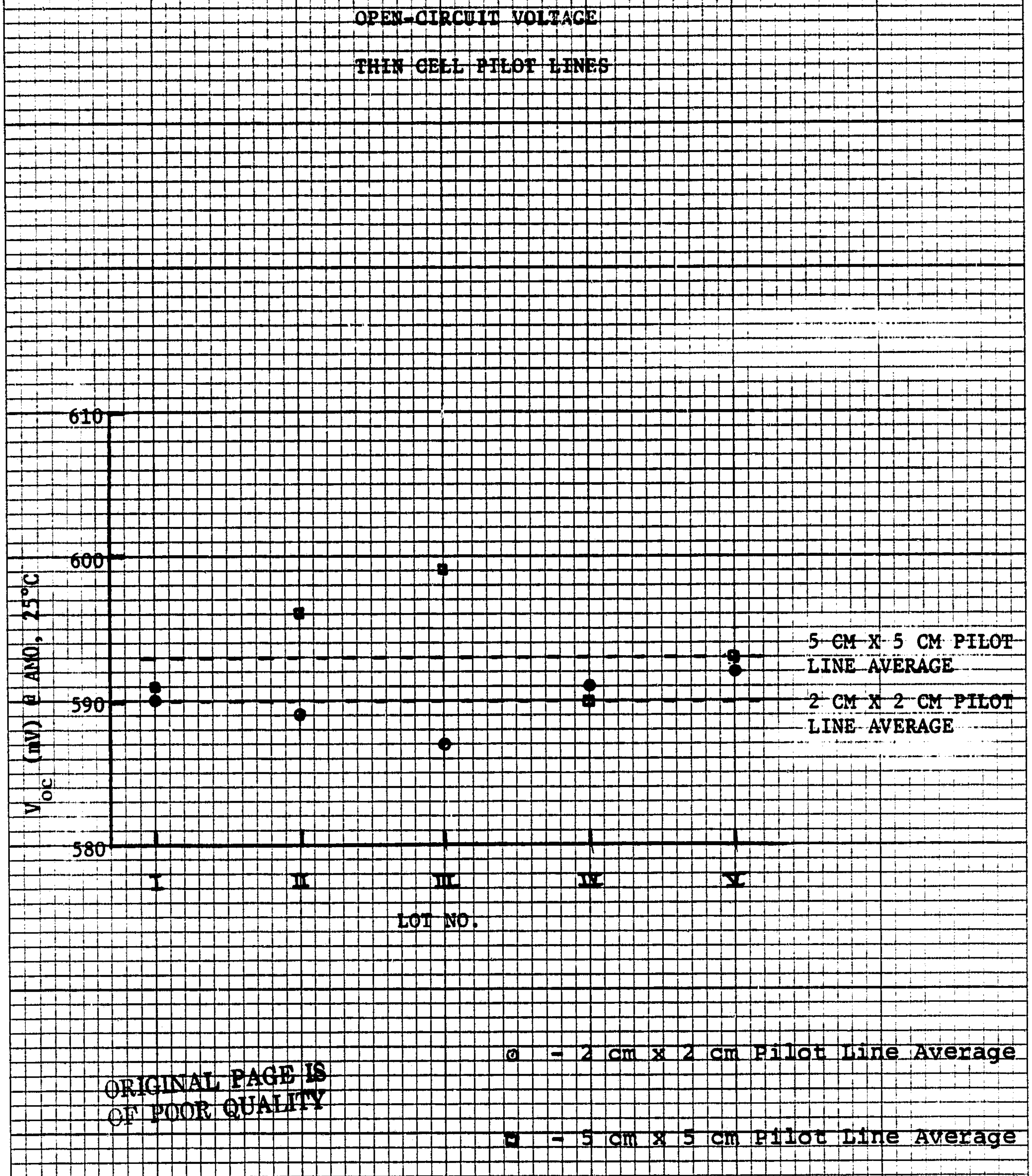
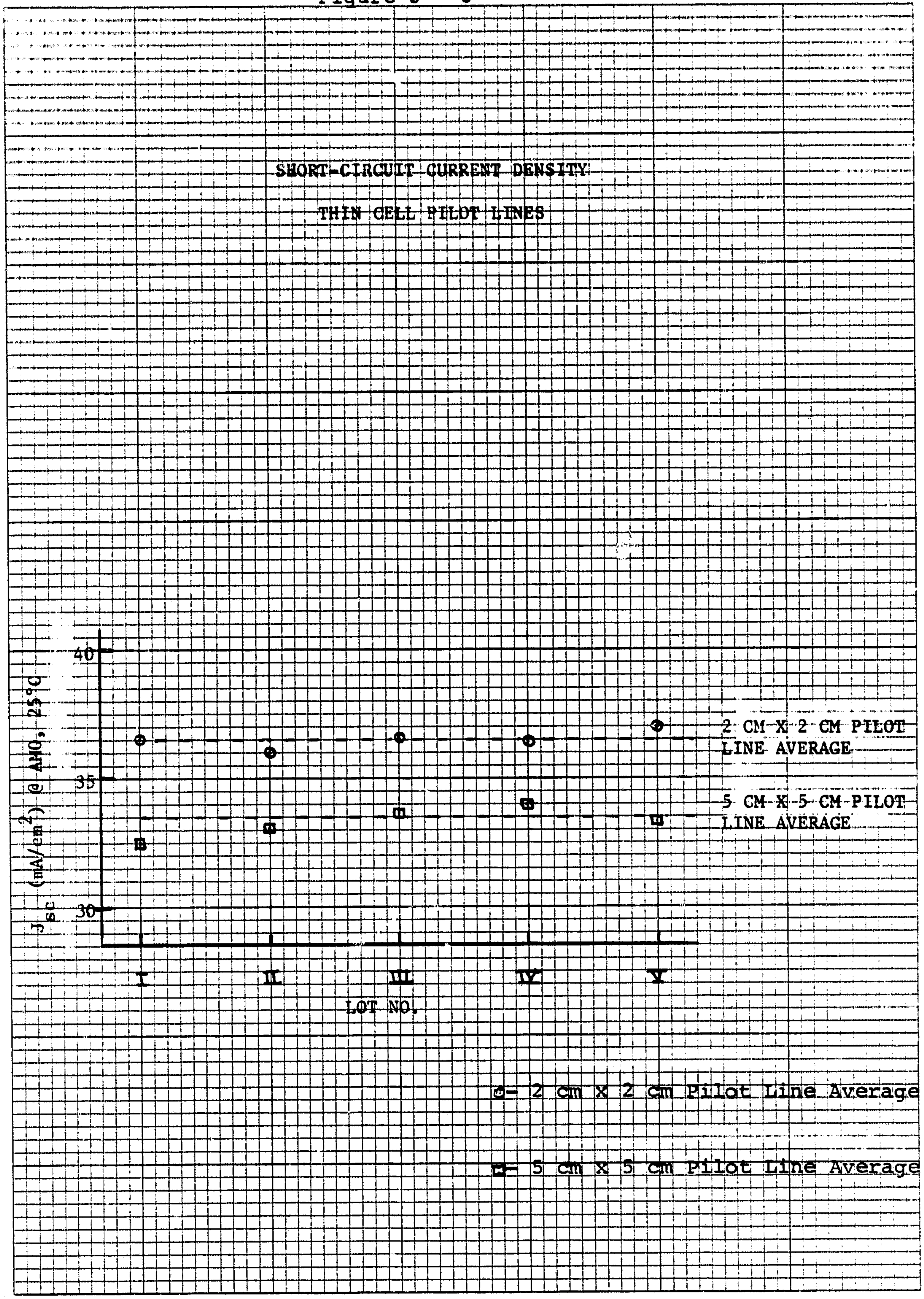

OPEN-CIRCUIT VOLTAGE
THIN CELL PILOT LINES
610
600
590
580
V_{OC} (mV) @ AM0, 25°C
I
II
III
IV
V
LOT NO.
5 CM X 5 CM PILOT LINE AVERAGE
2 CM X 2 CM PILOT LINE AVERAGE
● - 2 cm x 2 cm Pilot Line Average
■ - 5 cm x 5 cm Pilot Line Average

Figure 3 - 3


SHORT-CIRCUIT CURRENT DENSITY
THIN CELL PILOT LINES
40
35
30
J_{sc} (mA/cm^2) @ AMO, 25°C
I
II
III
IV
V
LOT NO.
2 CM X 2 CM PILOT LINE AVERAGE
5 CM X 5 CM PILOT LINE AVERAGE
2 cm X 2 cm Pilot Line Average
5 cm X 5 cm Pilot Line Average

Electrical Performance:

Cell electrical performance was measure using Xenon sources calibrated by reference cells. For the 2 cm x 2 cm Pilot Line cells a DEC/LAB 11/03 computer was used to control the I-V scan, to determine values of open-circuit voltage, short-circuit current, power and fill-factor, and to display the results. All measurements were made under AMO (135.3 mW/cm^2) conditions at 25°C. The minimum acceptable AMO power was established to be 60 mW for the 2 cm x 2 cm cells.

Cells from the 5 cm x 5 cm Pilot Line were tested for electrical performance using a Spectrolab X-25 Solar Simulator. The minimum acceptable power for a 5 cm x 5 cm Thin Cell was established to be 338 mW at AMO (135.3 mW/cm^2) at 25°C.

Mechanical Inspection:

The front contact of each cell was inspected to determine that less than 5% of the contact fingers were missing, that there was no evidence of contact bubbling or peeling, and that no busses or fingers had lifed. The rear contact was inspected to determine that silver had plated to more than 90% of the rear contact area and that there was no evidence of rear contact peeling or bubbling. The cells were inspected to determine that the cell area was within 0.5% of the nominal area. The same mechanical criteria were used for the 5 cm x 5 cm Pilct Line as for the 2 cm x 2 cm Pilot Line.

3.2.2 Process Step Loss Summary

Table 3-3 shows the losses, in number of cells, at each process step for each lot of the 2 cm x 2 cm Thin Cell Pilot Line. The losses are totals for all modes of loss, including breakage, improper processing, and rejection for electrical, mechanical or any other reason. Included in this table are the total number of cells lost at each process step for the complete Pilot Line, as well as the overall yield for each 2 cm x 2 cm Thin Cell lot and yield for the entire 2 cm x 2 cm Thin Cell Pilot Line, 38.3%.

More detail on the mode of loss can be found in Tables 3-4 and 3-5 which give the loss-reject mode for processing and testing, respectively, in the 2 cm x 2 cm Thin Cell Pilot Line.

Tables 3-6 and 3-7 present similar data on the process step losses and loss-reject modes for the 5 cm x 5 cm Thin Cell Pilot Line. The loss modes are similar to the 2 cm x 2 cm Thin Cell Pilot with the exception that the cells whose power were less that 338 mW (10% efficiency, AMO, 25^{o}C) were rejected. The overall yield of the 5 cm x 5 cm Thin Cell Pilot Line was 12.8%.

Table 3 - 3

PROCESS STEP LOSS SUMMARY: 2 CM X 2 CM PILOT LINE

LOT NO.	I	II	III	IV	V	PILOT LINE TOTAL
ETCH	27	57	20	9	12	125
DIFFUSE	0	42	24	12	6	84
HF ETCH	6	18	0	3	30	57
PASTE	9	18	12	6	9	54
ALLOY	18	6	0	0	0	24
HCl ETCH	87	91	24	12	48	262
BACK EVAP	48	9	36	18	0	111
RESIST	90	114	39	24	24	291
EXPOSE	18	12	12	0	5	47
DEVELOP	3	18	36	6	18	81
FRONT EVAP	12	18	24	6	6	66
LIFT-OFF	203	109	31	36	60	439
PLATING	81	94	210	192	202	779
SINTER	3	2	0	43	6	54
CUT	95	126	99	68	120	508
CLEAN	15	9	8	14	6	52
IN-LINE QC	66	49	53	30	35	233
AR COAT	23	24	60	24	35	166
SINTER	6	5	0	2	3	16
TEST	49	32	46	76	51	254
TOTAL LOST	859	853	734	581	676	3703
STARTS	1200	1200	1200	1200	1200	6000
YIELD (%)	28.4	28.9	38.8	51.6	43.7	38.3

Table 3 - 4

PROCESS LOSS - REJECT MODES: 2 CM X 2 CM PILOT LINE

MODE	I	II	III	IV	V	PILOT LINE TOTAL
A	507	463	363	245	304	1882
B	76	75	41	17	71	280
C	31	51	24	-	-	106
D	12	-	-	-	-	12
E	-	-	174	-	-	174
F	-	6	-	-	-	6
G	6	-	-	-	5	11
H	182	229	78	169	172	830
I	10	5	14	82	94	205
J	-	-	-	-	2	2
K	23	13	21	43	10	110
L	12	11	19	25	18	85
ALL MODES	859	853	734	581	676	3703

<u>LOSS CATEGORY</u>

A - BROKEN BY OPERATOR

B - BROKEN IN SPIN

C - ETCH IMPERFECTION

D - METAL SPATTER

E - IMPROPER EVAPORATION

F - RESIST FAILURE

G - PLATING DEFECTS

H - FRONT CONTACT

I - BACK CONTACT

J - IMPROPER AR COATING

K - MECHANICAL REJECT

L - ELECTRICAL REJECT

Table 3 - 5

TEST REJECT MODES: 2 CM X 2 CM PILOT LINE

LOT NO.	I	II	III	IV	V	PILOT LINE TOTAL
ELECTRICAL	12	11	19	25	18	85
MECHANICAL	23	13	21	43	10	110
METALLIZATION	10	5	2	4	22	43
BROKE IN TEST	4	3	4	4	1	16
TOTAL	49	32	46	76	51	254

Table 3 - 6

PROCESS STEP LOSS SUMMARY: 5 CM X 5 CM PILOT LINE

LOT NO.	I	II	III	IV	V	PILOT LINE TOTAL
ETCH	24	39	54	38	4	159
DIFFUSE	4	2	11	1	5	23
HF ETCH	0	2	0	9	8	19
PASTE	19	12	3	2	2	38
ALLOY	4	8	17	4	4	37
HCl ETCH	76	34	6	8	12	136
BACK EVAP	6	7	3	7	51	74
PLATING	76	33	39	18	36	202
REINFORCE	0	0	0	0	0	0
RESIST	0	1	3	9	0	13
EXPOSE	0	2	14	3	0	19
DEVELOP	0	0	0	0	0	0
FRONT EVAP	20	8	17	43	3	91
LIFT-OFF	0	1	0	7	0	8
PLATING	13	62	52	34	3	164
CUT	9	27	8	23	10	77
CLEAN	16	20	18	29	7	90
AR COAT	5	4	4	2	1	16
SINTER	2	3	0	3	2	10
TEST	4	4	9	10	2	29
TOTAL LOST	278	269	258	250	150	1205
STARTS	300	300	300	300	182	1382
YIELD (%)	7.3	10.3	14.0	16.7	17.6	12.8

Table 3 - 7

PROCESS LOSS - REJECT MODES: 5 CM X 5 CM PILOT LINE

MODE	I	II	III	IV	V	PILOT LINE TOTAL
A	109	157	171	192	116	745
B	55	22	6	13	22	118
C	6	4	-	-	-	10
D	-	-	-	-	3	3
E	5	49	40	8	5	107
F	18	29	8	20	4	79
G	-	-	9	-	-	9
H	-	-	-	-	-	-
I	-	-	-	4	-	4
J	1	2	1	1	-	5
K	84	6	23	12	-	125
ALL MODES	278	269	258	250	150	1205

LOSS CATEGORY

A - BROKEN BY OPERATOR

B - BROKEN IN SPIN

C - ETCH IMPERFECTION

D - BAD EVAPORATION

E - PLATING REJECT

F - FRONT CONTACT

G - BACK CONTACT

H - IMPROPER AR COATING

I - REPROCESS ADDED

J - ELECTRICAL REJECT (η<10% AMO)

K - MISCELLANEOUS

3.2.3 Tape Peel Tests

Since the integrity of the front contact metallization is essential for good operation of the cells, tape peel tests were performed (using the standard technique) on thick cells which were processed together with the thin cell lots. Table 3-8 gives the results of these tests, in number of failed cells, where a failure meant that more than 5% of the good contact fingers were lost. The average failure rate of the tape peel test for monitor cells processed with the 2 cm x 2 cm Thin Cell Pilot Line lots was 4.3%, but only one cell failed in two lots (II and V) and Lot IV had no failures.

Table 3 - 8

TAPE PEEL TEST: 2 CM X 2 CM PILOT LINE

LOT NO.	CELLS TESTED	FAILED	FAILURE RATE
II	42	1	2.4%
III	38	4	10.5%
IV	24	0	0.0%
V	35	1	2.9%
PILOT LINE	139	6	4.3%

3.3 Costs

Production cost breakdowns for the 2 cm x 2 cm and 5 cm x 5 cm ultra-thin Pilot Line cells are shown in Tables 3-9 and 3-10. A delivered 2 cm x 2 cm ultra-thin cell cost $6.15 to produce. Due to the low yield, a 5 cm x 5 cm ultra-thin Pilot Line cell cost $90.67 to produce. It should be pointed out that these costs are based on the actual fabrication and inspection procedures which were used on the Pilot Line. This does not include the additional documentation and space qualification cos ; which would normally be applied.

Table 3-9

PILOT LINE

EXPERIENCED COST BREAKDOWN
FOR 2 CM X 2 CM ULTRA-THIN CELLS

CATEGORY	COST PER CELL, $	PERCENT OF TOTAL
SILICON	$ 1.15	18.7
MATERIALS	1.35	22.0
LABOR	1.49	24.2
OVERHEAD	2.16	35.1
TOTAL	6.15	100.0
$6.15 WAS THE COST OF PRODUCING A GOOD CELL*		

*Cost based on actual procedures used (Space qualification procedures were not used).

Table 3-10

PILOT LINE

EXPERIENCED COST BREAKDOWN
FOR 5 CM X 5 CM ULTRA-THIN CELLS

CATEGORY	COST PER CELL, $	PERCENT OF TOTAL
SILICON	22.88	25.2
MATERIALS	19.35	21.3
LABOR	19.77	21.8
OVERHEAD	28.67	31.6
TOTAL	90.67	99.9
$90.67 WAS THE COST OF PRODUCING A GOOD CELL*		

*Cost based on actual procedures used (Space qualification procedures were not used).

4. Discussion of Results and Projections

4.1. Cell Characteristics

As mentioned previously, and as shown in Figure 3-1, the power density for cells from the 2 cm x 2 cm Thin Cell Pilot Line did not deviate much from the Pilot Line average of 16.8 mW/cm^2. In contrast to this, the power density of 5 cm x 5 cm thin cells improved as experience was gained, increasing from 14.9 mW/cm^2 in the first lot to a high of 15.7 mW/cm^2 in Lot III. Lots IV and V maintained this power density, while showing improved yields. The average power density of the 5 cm x 5 cm thin cells, which at 15.5 mW/cm^2 is significantly less than the power density of the 2 cm x 2 cm cells, is the result of a reduced current density since the open-circuit voltages are essentially the same (590 mV for 2 cm x 2 cm cells vs. 593 mV for 5 cm x 5 cm cells) and the fill factors are the same (0.78) in both types of cells. As shown in Figure 3-3 the current densities do not vary from lot to lot for either type of cell, but the average current density of the 5 cm x 5 cm thin cells is about 8% less than the current density of the 2 cm x 2 cm thin cells. The difference is probably due to increased shadowing by the 5 cm x 5 cm metallization pattern. Although by design the 5 cm x 5 cm pattern shadow loss is only slightly worse than the 2 cm x 2 cm pattern

shadow loss, the 5 cm x 5 cm wafers were overexposed during photolithography to improve pattern definition and contact integrity. However, while improving contact adhesion, overexposure also widens the pattern and increases shadowing. This would account for the difference in current density between the two Pilot Lines. After accounting for the shadowing, the average current densities are still somewhat low, compared to values reported earlier for thin cells, and this is very likely the result of a reduced bulk lifetime.

Although many cells had open-circuit voltages greater than 600 mV, the Pilot Line averages were significantly below this value. We believe that the reason for these somewhat lower than expected open-circuit voltages is due to a less than optimum alloyed back surface field. Prior to the 2 cm x 2 cm Thin Cell Pilot Line operation, a considerable amount of effort was expended in attempting to optimize the screen-print, alloy, and clean-up steps with respect to performance and breakage. It was found that breakage in the alloy clean-up was related to the amount of warpage in the alloyed wafers, and that this warpage increased as the thickness of the aluminum paste layer increased. As a consequence, during the 2 cm x 2 cm Thin Cell Pilot Line we attempted to keep the paste thickness thin in order to minimize the breakage due to wafer warpage in the alloy clean-up step. However, decreasing the thickness of the paste layer has been subsequently found to result in an alloy layer that may have unalloyed regions which

will reduce the effect of the back surface field, resulting in decreased open-circuit voltages. For the 2 cm x 2 cm Thin Cell Pilot Line, only 262 of the cells that reached the alloy step (5680), or 4.6%, were lost due to breakage in the alloy and alloy clean-up steps. This should be compared to losses of more than 30% in these same steps in small test lots fabricated prior to the Pilot Line. The open-circuit voltage for 5 cm x 5 cm cells is somewhat higher, indicating that the paste layer was perhaps a little thicker.

The specific power of the average 2 cm x 2 cm Pilot Line Cell, 1.30 kW/kg, is considerably higher than that of the average 5 cm x 5 cm Pilot Line Cell, 0.95 kW/kg. This is due principally to the higher power density of the 2 cm x 2 cm cells.

4.2 Process Yields

As shown in Table 3-3 the overall yield of the 2 cm x 2 cm Thin Cell Pilot Line improved substantially as experience in handling the 2 mil thick cells was gained. The best yield was over 51%, and the average for the five lots of the Pilot Line was better than 38%. The modes of loss are enumerated in Table 3-4; most losses were due to handling breakage (51%), followed by front contact failures (22%), and breakage in the spin dryers (8%). Unlike the losses due to front contact failures and spin-dryer breakage which

remained fairly consistent, handling breakage decreased from 507 cells (or 42% of the starts) in the first lot to less than half that value, 245 cells, in the fourth lot. Since breakage caused the most losses, and showed the greatest improvement, a more detailed analysis of breakage for each process step is shown in Table 4-1. For the 2 cm x 2 cm Thin Cell Pilot Line the steps which had the most breakage were: lift-off, HCl etch after alloy, cutting, resist spinning, and AR coating. The first two, lift-off and post-alloy etch, decreased drastically as the Pilot Line progressed, as shown in Figure 4-1. The decrease in breakage at lift-off is associated with operator experience; that at the HCl etch is due to changes in processing parameters (controlling the paste thickness) as well as operator experience. The remainder of the processes show less improvement with time or experience.

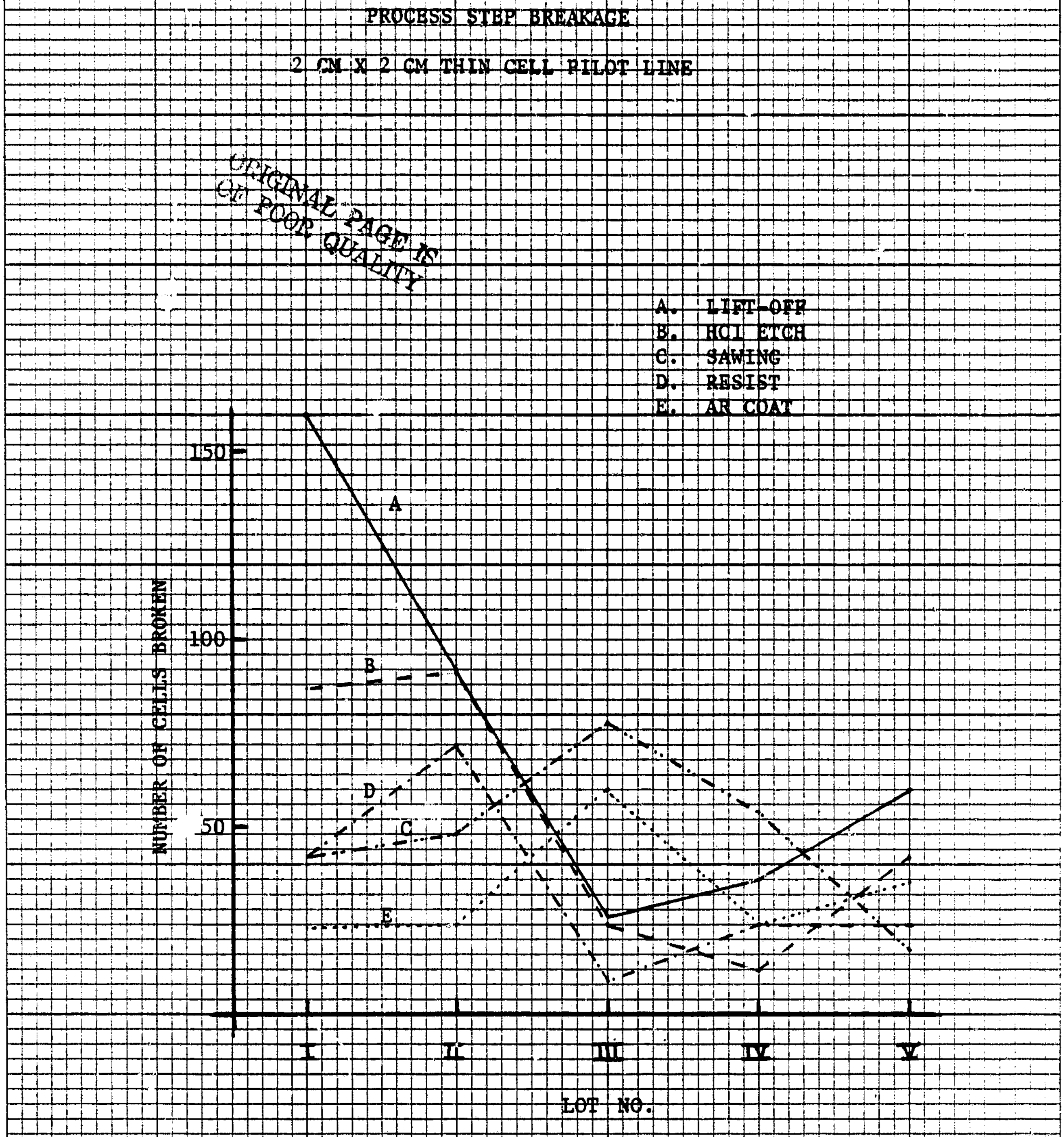
Comparison of Tables 3-3 and 4-1 indicates those steps which might be improved with operator experience and those which are dependent on processing improvements. In the Pilot Line, 779 cells were lost in plating; of these 136 were broken and the rest were rejected because of bad metallization. This implies that previous improvements in this step by redesigning the plating racks for less breakage were successful. 508 cells were lost at

Table 4 - 1

PROCESS STEP BREAKAGE: 2 CM X 2 CM PILOT LINE

LOT NO.	I	II	III	IV	V	PILOT LINE TOTAL
ETCH	8	12	8	9	12	49
DIFFUSE	-	42	12	12	6	72
HF ETCH	6	-	-	-	6	12
PASTE	9	18	12	6	9	54
ALLOY	6	-	-	-	-	6
HCl ETCH	87	91	24	12	42	256
BACK EVAP	48	9	36	18	-	111
RESIST	42	72	9	24	24	171
EXPOSE	18	12	12	-	5	47
DEVELOP	3	12	30	6	-	51
FRONT EVAP	12	12	24	6	6	60
LIFT-OFF	160	91	26	36	60	373
PLATING	30	10	24	-	72	136
SINTER	3	2	-	32	6	43
CUT	42	48	74	54	17	235
CLEAN	-	-	8	-	-	8
IN-LINE QC	-	-	-	-	-	-
AR COAT	23	24	60	24	35	166
SINTER	6	5	-	2	3	16
TEST	4	3	4	4	1	16

Figure 4 - 1



PROCESS STEP BREAKAGE
2 CM X 2 CM THIN CELL PILOT LINE
A. LIFT-OFF
B. HCl ETCH
C. SAWING
D. RESIST
E. AR COAT
150
100
50
NUMBER OF CELLS BROKEN
A
B
C
D
E
I
II
III
IV
V
LOT NO.

the cutting step; 235 were broken, and the remainder were rejected because of contact failures. Most of the breakage at this step was due to problems with the equipment, and, consequently, could be reduced. A total of 439 cells were lost at lift-off, 373 due to breakage. As mentioned previously, breakage at this step decreased substantially as experience was gained. Resist spinning claimed 291 cells, of which 171 were broken. The remainder were broken in the spin dryer. Losses due to both modes decreased as the Pilot Line progressed. Nearly all of the losses in the post-alloy HCl etch were due to breakage. However, the breakage decreased as the Pilot Line progressed but, more importantly, was less than 5% of the starts, whereas in earlier small production runs the losses at this step were closer to 30%. Losses due to breakage by the screen printer were negligible (54) as a result of redesigning the screen printer chuck to hold the wafers more gently and securely.

As mentioned previously, the overall yield of the 2 cm x 2 cm Pilot Line was better than 38%, and the best lot yield was over 51%. An estimate for yield assuming the personnel were experienced and that processes and equipment were optimized was made by using the lowest number of losses at each step in Table 3-3. This estimated

yield is 70%, and should be considered an upper limit on yield using existing processes and equipment and experienced personnel.

Table 4-2 gives similar data on breakage for the 5 cm x 5 cm Pilot Line; Figure 4-2 plots the breakage for the highest loss steps - etching, back plating, cleaning, post-alloy etch, and final clean-up. The values plotted for Lot V are scaled up to match the number of starts for the other four lots. The losses at the thinning etch increased substantially in the middle of the Pilot Line effort, then decreased to below its initial value.

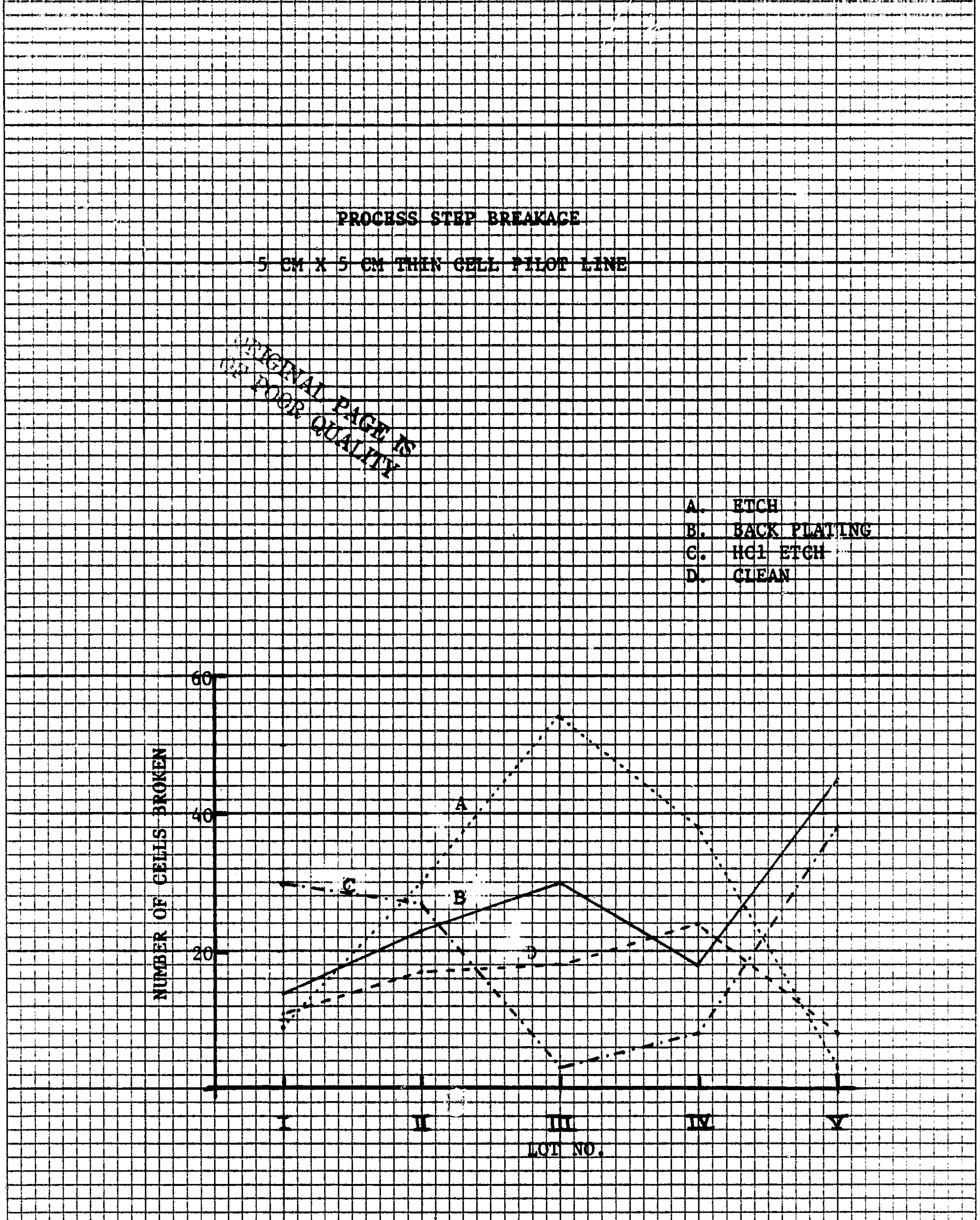
The losses in Lot V at the back plating are close to the average for the previous four lots, while the post-alloy etch losses are actually very low in the third and fourth lots, after some experience has been gained. Losses at the final clean-up are relatively consistent throughout the 5 cm x 5 cm Pilot Line. As shown in Table 3-6, the lot yield of the 5 cm x 5 cm Thin Cell Pilot Line improved from only 7% in the first lot to 17% or better in the best two lots. While low in comparison to the yield of the 2 cm x 2 cm Thin Cell Pilot Line, this yield is not surprising considering that this was the first 5 cm x 5 cm Thin Cell Pilot Line effort, and considering the short duration (5 days)

Table 4 - 2

PROCESS STEP BREAKAGE: 5 CM X 5 CM PILOT LINE

LOT NO.	I	II	III	IV	V	PILOT LINE TOTAL
ETCH	9	30	54	38	2	133
DIFFUSE	4	2	5	1	2	14
HF ETCH	-	2	-	3	-	5
PASTE	12	12	3	2	2	31
ALLOY	4	2	14	4	4	28
HCl ETCH	30	27	3	8	23	91
BACK EVAP	6	7	3	7	40	63
PLATING	14	23	30	18	27	112
REINFORCE	-	-	-	-	-	-
RESIST	-	1	-	-	-	1
EXPOSE	-	2	-	-	-	2
DEVELOP	-	-	-	-	-	-
FRONT EVAP	-	-	17	39	-	56
LIFT-OFF	-	1	-	7	-	8
PLATING	6	16	12	18	1	53
CUT	3	6	-	9	5	23
CLEAN	11	17	18	24	5	75
AR COAT	5	4	4	2	1	16
SINTER	2	3	-	3	2	10
TEST	3	2	8	9	2	24

Figure 4 - 2



PROCESS STEP BREAKAGE
5 CM X 5 CM THIN CELL PILOT LINE
ORIGINAL PAGE IS OF POOR QUALITY
A. ETCH
B. BACK PLATING
C. HCl ETCH
D. CLEAN
NUMBER OF CELLS BROKEN
60
40
20
A
B
C
D
I
II
III
IV
V
LOT NO.

of the operation. An estimated yield for an optimized line with experienced operators and processes, obtained by taking the fewest losses for each step from the first four lots, is 64%.

4.3 Fabricability

As mentioned previously, the integrity of the front contact metallization was considered to be a very important aspect of thin cell processing. To test the quality of the front contacts, thick wafers were processed along with the thin cell wafers. Very few cells failed the tape peel test as indicated in Table 3-8. To further test front contact integrity, electrical or mechanical reject thin cells were tested by the tape peel test (after sticking them to a table). Once again, very few cells failed the test, indicating that, if fingers were not visibly lifting, the contacts had good adherence.

The improvements in the contact integrity are due to changes in wafer processing at the photolithographic, metal evaporation, and plating steps. First, a previously used HF etch step after photolithographic pattern development and prior to the front Ti/Pd evaporation was omitted. Removal of the thin room-temperature oxide between the metallization and the front surface is unnecessary since sintering causes good

electrical contact through the oxide. Second, increased exposure time improved adhesion, however, at the expense of some increase in shadowing. And finally, introduction of a low temperature heat treatment (150°C for 20 minutes) after the front Ti/Pd evaporation and prior to Ag plating resulted in better contact integrity.

Breakage of wafers during processing was reduced by the following changes: (1) at the screen-printing step, a new vacuum chuck was designed and fabricated which held the wafers more securely and uniformly; (2) the screenprinter was adjusted to produce thinner paste layers resulting in less warped wafers after alloy, which reduced breakage during the alloy clean-up; (3) at the photoresist spin-on step, the wafers were cushioned on the chuck by a plastic film which minimized the effects of lumps left from the Al alloy; and (4) the plating racks were redesigned to improve the wafer hold-down (steel racks with magnetic hold-down) and minimize the Ag build-up.

Further improvements in the thin cell fabricability could be obtained by developing more controlled wet-processing steps. For example, it might be possible to perfrom the metallization lift-off step in a spin-wash system where cassettes of wafers would be processed, rather than cleaning each wafer individually.

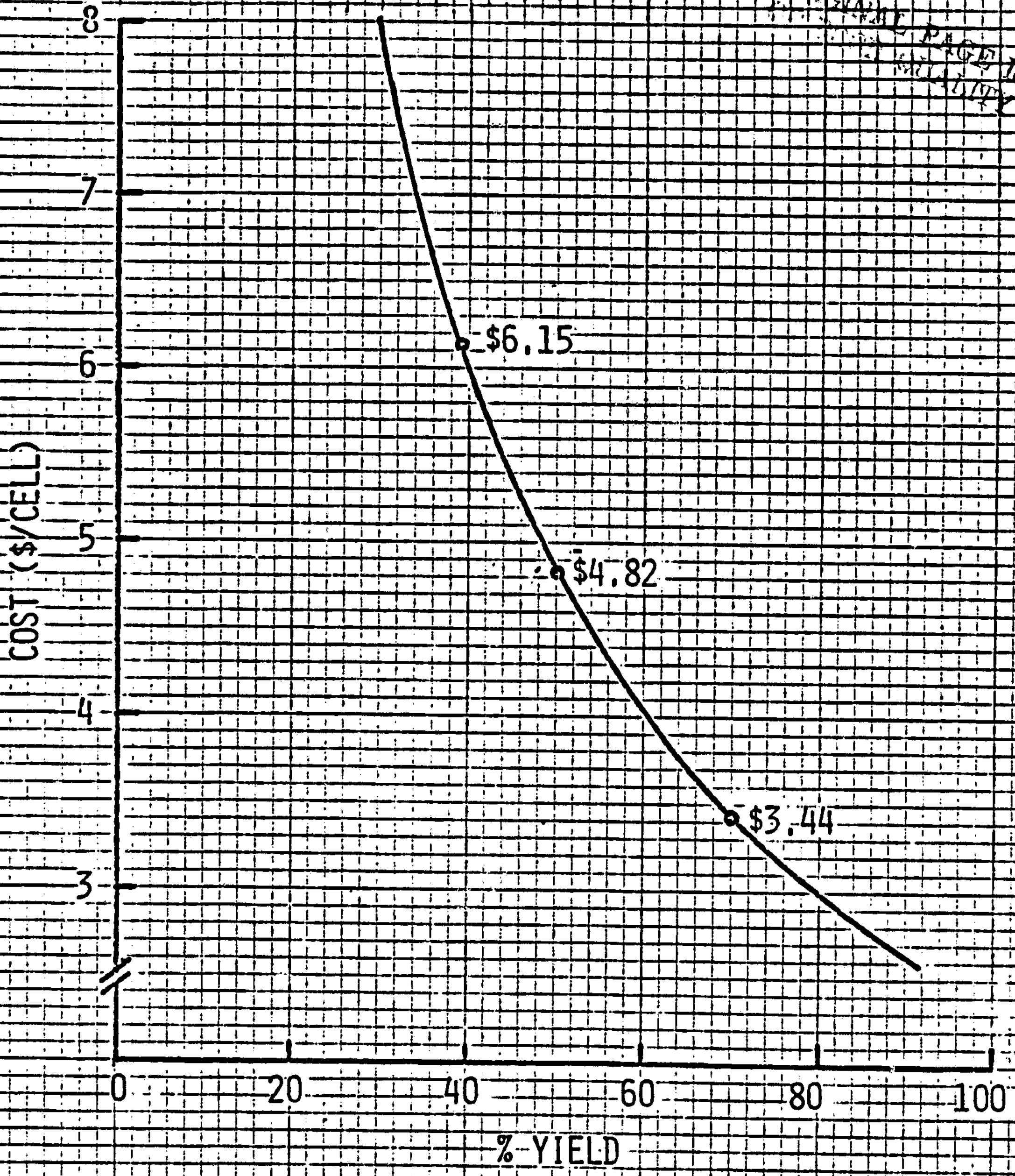
4.4 Costs

As mentioned previously, the cost of a 2 cm x 2 cm Ultra-Thin Cell was $6.15; while, because of the low yield, a 5 cm x 5 cm Ultra-Thin Cell cost $90.67. The experienced cost breakdowns are shown in Tables 3-9 and 3-10. In analyzing the Pilot Line yields, we estimated that the best yield of the 2 cm x 2 cm Thin Cell Pilot Line, using existing technology and procedures and experienced personnel, would be approximately 70%. The cost vs. yield curve for the 2 cm x 2 cm Ultra-Thin Cells is shown in Figure 4-3. The cost of a 2 cm x 2 cm thin cell with a line yield of 50% is $4.82; if the yield improved to the projected 70%, the cost would decrease to $3.44, which translates to about $51 per peak watt (AM0).

Although the cost of a 5 cm x 5 cm Ultra-Thin Pilot Line Cell was over $90, we estimate that the cost per cell would decrease to $17.87 if a yield of 64% were achieved, as shown in the cost-yield curve in Figure 4-4. This yield was estimated as the best possible using the experience of the Pilot Line. Cells produced at this yield with the present efficiency would result in costs of about $46 per peak watt (AM0).

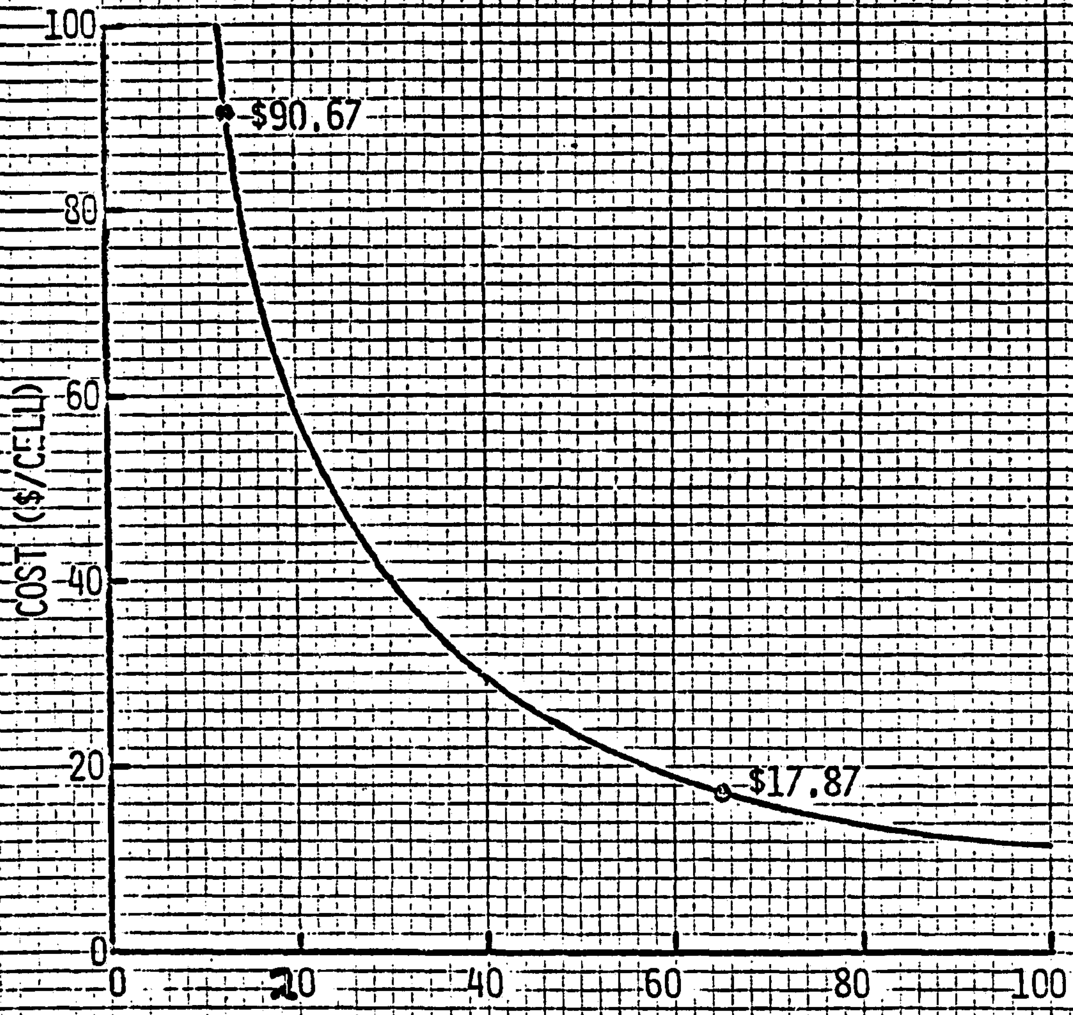
The cell cost as shown here is the actual cost of producing thin cells on these two Pilot Line runs. Additional quality assurance checks would be necessary to produce space-qualified Ultra-Thin Cells, and consequently the costs would be greater.

Figure 4-3



COST-YIELD-CURVE FOR 2-CM-X-2-CM-ULTRATHIN-CELLS

Figure 4-4



COST-YIELD CURVE FOR 5 CM X 5 CM ULTRATHIN CELLS

5. CONCLUSIONS

Substantial improvement in the performance of cells and in the yield of the Ultra-thin Cell Pilot Lines were obtained. The overall yield of the 2 cm x 2 cm Pilot Line was better than 38%, while the best lot yield was greater than 51%. The average power density of the 2 cm x 2 cm Ultra-thin cell was approximately 16.8 mW/cm^2 giving an average AMO (at 25^oC) efficiency of 12.4%. The lot yield of the 5 cm x 5 cm Pilot Line improved from only 7% at the beginning of the Pilot Line to better than 17% as experience was gained, giving an overall Pilot Line yield of more than 12%. The average 5 cm x 5 cm Ultra-thin cell had an AMO efficiency (at 25^oC) of 11.5%.

The yield of the 5 cm x 5 cm Pilot Line is low for two reasons. First, this effort was the first time a Pilot Line to produce large-area high-efficiency thin cells was ever attempted. The improvement in yield during the Pilot Line is a result of experience gained in handling these large area cells. Second, six 2 cm x 2 cm cells were obtained from each 3" diameter wafer. If the wafer should break in process, up to five cells may be salvaged from the pieces. However, there is only one 5 cm x 5 cm cell per 3" diameter wafer. Obviously, if the wafer breaks in the process sequence, the cell is totally lost. Therefore, yield is much more strongly a function of breakage for 5 cm x 5 cm thin cells than for 2 cm x 2 cm

thin cells. The yield of the 5 cm x 5 cm Pilot Line was low because of breakage, and improved mainly due to decreased breakage.

Improvements in performance and contact integrity are due to use of a screen-printed aluminum back surface field and changes in wafer processing at the photolithographic, metal evaporation, and plating steps respectively. Improvements in yield are essentially due to gentler techniques for securing wafers to the screen-printer chuck, to the photoresist spinner chuck, and to the Ag plating racks. Further improvement could be obtained by developing more controlled wet-processing steps wherein cassettes of wafers are handled, rather than individual wafers.

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